COMMUNICATION AND LOCALIZATION WITH HEARING PROTECTORS

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ABSTRACT

Hearing protectors are frequently used to preserve hearing when personnel are working in areas of high pulse and/or continuous noise. Speech communication and auditory localization are two important functions of the auditory system, which potentially are impeded when circumaural and/or insert hearing protectors are used. This paper describes the measured effects of hearing protectors on speech communication and auditory localization. The effects on auditory localization include interactions with the visual system and the resulting effects on locating potential objects which may pose a threat to the listener. Implications for military and civilian users of hearing protectors are discussed.

INTRODUCTION

Impulse noise has been a major source of risk for hearing damage. Thousands of military personnel are routinely exposed to small arms, mortar, and/or artillery fire during training. The levels range from approximately 140 dB to over 190 dB. Hearing conservation programs have been established to regulate the exposures of these personnel to both impulse and continuous noise. Most often, the noise level has not been controlled at the source. The normal method of mitigating the noise exposures has been personal hearing protection equipment such as earmuffs and/or earplugs. These types of devices have been optimized over the past forty years in order to provide maximum noise attenuation. However, little, except for a few electronic level dependent earmuffs, has been done to promote speech communication or auditory localization with hearing protectors. Yet speech communication and auditory localization provide significant contact with the environment and are essential factors in safety and ultimately survival in many situations. Hearing protectors affect the auditory signal which reaches the ear. The effect is frequency dependent and often spatially dependent.

Speech communication intelligibility is primarily dependent on the signal-to-noise ratio. For a given noise level, speech intelligibility will increase with increasing speech level until the speech level is approximately 105 dB. If the speech level is increased above 105 dB, the speech signal is distorted in the auditory system and no additional gains are realized in speech intelligibility. One exception is the potential use of an earplug under a communication headset or the use of either earmuffs or earplugs with a public address or sound reinforcement system. In this instance, the speech level and the noise level will be reduced by the hearing protectors. However, the speech level can be increased by using the communication headset or public address system up to a level of 105 dB at the ear (i.e. under the earplug or earmuff), thereby realizing a theoretical gain in the signal-to-noise ratio equal to the attenuation of the hearing protector. This gain is only realized if the quality of the speech can be maintained and produced at these high levels. For an example, if a 25 dB earplug were being used, low distortion, 130 dB (105 dB + 25 dB) speech would need to be produced. This is simple in theory but difficult in practice. Additionally, in a free-field environment, speech communication is aided by spatial content such as experienced at a "cocktail party." This spatial content gives an apparent 2.5 dB improvement in the signal-to-ratio.

A few studies have investigated the effects of hearing protectors on the spatial components of speech, auditory warning signals, and other auditory stimuli. Studies by Atherley & Noble (1970), Noble & Russell (1972), Abel & Armstrong (1993), Vause & Grantham (1999), showed that localization in azimuth is degraded when earmuffs or earplugs are used. The main errors are in front-back or back-front confusions (Vause & Grantham, 1999). Atherley and Noble (1970) found that listeners localizing a 1000 Hz puretone in azimuth made more errors with an earmuff than without. Additionally, listeners using the earmuffs frequently perceived the source as coming from the hemifield contralateral to its actual position. A study

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by Abel and Hay (1996) found a similar effect with a stimulus frequency of 4000 Hz but not with a 500 Hz stimulus. Noble (1981) demonstrated that listeners localize as well in azimuth with earplugs or earmuffs as they do with an open ear when head motion is permitted. He reported slower reaction times with the hearing protectors and reduced capability in localization in elevation. There is a potential safety hazard in the disruption of auditory localization by hearing protectors. Wightman & Kistler (1997) described the physical properties of individual hearing protectors that result in modification of monaural and binaural spectral cues important for auditory localization. Industrial accidents and a few fatalities have been attributed to the inability to hear and/or localize critical audio cues in the immediate environment (Laroche, Ross, Lefebvre, & Larocque, 1995).

These errors are due to the disruptions of the auditory localization cues by the hearing protectors. Oldfield & Parker found in 1984(b) that the interaural time delay was one of the dominant cues for localization in azimuth. However, interaural time delay alone does not allow resolution to a single position. Addition of either head related spectral cues and/or head motion will allow the ambiguity to be resolved. These spectral cues are due to reflections of sound wave by the torso, shoulder, head, and pinnae. Musicant & Butler, 1984, found that the pinnae aid in resolving front-back by producing different spectral cues. Roffler & Butler (1968) also identified these spectral cues to be the primary cue for localization in elevation. Disruption of the shape, volume, etc. of the pinnae would therefore disrupt the formation of these spectral cues and thereby degrade the listener's ability to resolve the source's location in both front-back and up-down directions. However, almost no studies of the effects of hearing protectors on localization have included elevation as part of the study.

The objective of this paper was to describe a series of laboratory experiments which investigate the effects of hearing protectors on speech communication and auditory localization.

METHOD - DATA - DISCUSSION

Each of the studies will be presented individually in the format of method-data-discussion. The subject qualifications for all the studies are described.

Subjects

All volunteer subjects used in the described experiments were recruited from the general civilian population and were paid for their participation. All subjects exhibited pure tone audiograms demonstrating hearing levels equal to or better than 15 dB HL at 125, 250, 500, 1K, 2K, 4K, and 8 KHz. Additionally, they had no abnormalities in their external ear canal and tympanic membrane, and had normal middle ear function as verified by a laboratory research audiologist. Subjects in the auditory/visual interaction experiments also exhibited uncorrected 20/20 visual acuity. The talkers used in the speech intelligibility studies exhibited no strong regional accents. All subjects were native speakers of American English. The number and sex of subjects is described in the experimental design section. All subjects trained for a minimum of four hours on the task, speech intelligibility or localization, before formal data collection was initiated. The subjects also received a bi-weekly audiogram to check for any short-term and/or long term shifts in hearing.

EXPERIMENT SUBGROUP 1 - SPEECH INTELLIGIBILITY

Equipment

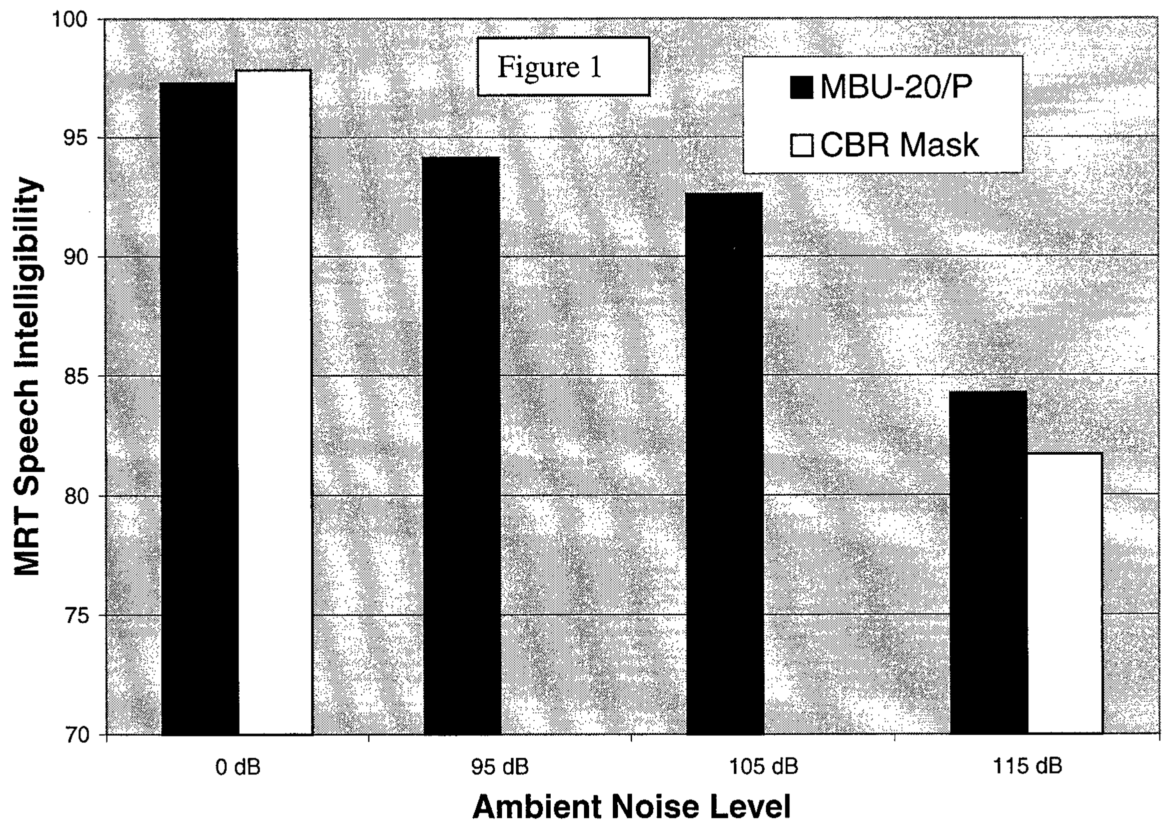
All speech intelligibility experiments were conducted in the Air Force Research Laboratory's (AFRL) Voice Communication Research and Evaluation Facility. This computer based human stimulus and response data facility supports ten simultaneous subjects in an ambient controllable acoustic environment. The calibrated sound field can be varied between a minimum of 45 dB and a maximum of 130 dB. Other AFRL human acoustic facilities are capable of generating sound fields up to 142 dB. The facility gives each talker a VU meter to aid in maintaining consistency of vocal effort during the experiment. Each listener has an individual volume control to adjust the speech to the most comfortable/highest intelligibility listening level.

Experiment A – Speech intelligibility with masks

Design This experiment used five talkers and five listeners, three male and two female. It was a within subjects design, with each subject participating in all experimental conditions. The Modified Rhyme Test (MRT) (ANSI S3.1-1989) was used to measure speech intelligibility. Two different masks were used. The first, the normal oxygen mask, the MBU-20/P, and the second, the chemical-biological-radiation (CBR) mask. The talkers were in a variable ambient noise environment which was an independent variable with four values, 0 dB, 95 dB, 105 dB, and 115 dB. The listeners were in a quiet environment. The CBR mask was measured only at the 0 dB and 115 dB values since it interfered with hearing protection and the subjects' exposures needed to be limited.

Results The results are shown in figure 1. For both masks the speech intelligibility varied with the ambient noise level. At the 115 dB noise level, the speech intelligibility was above 80%.

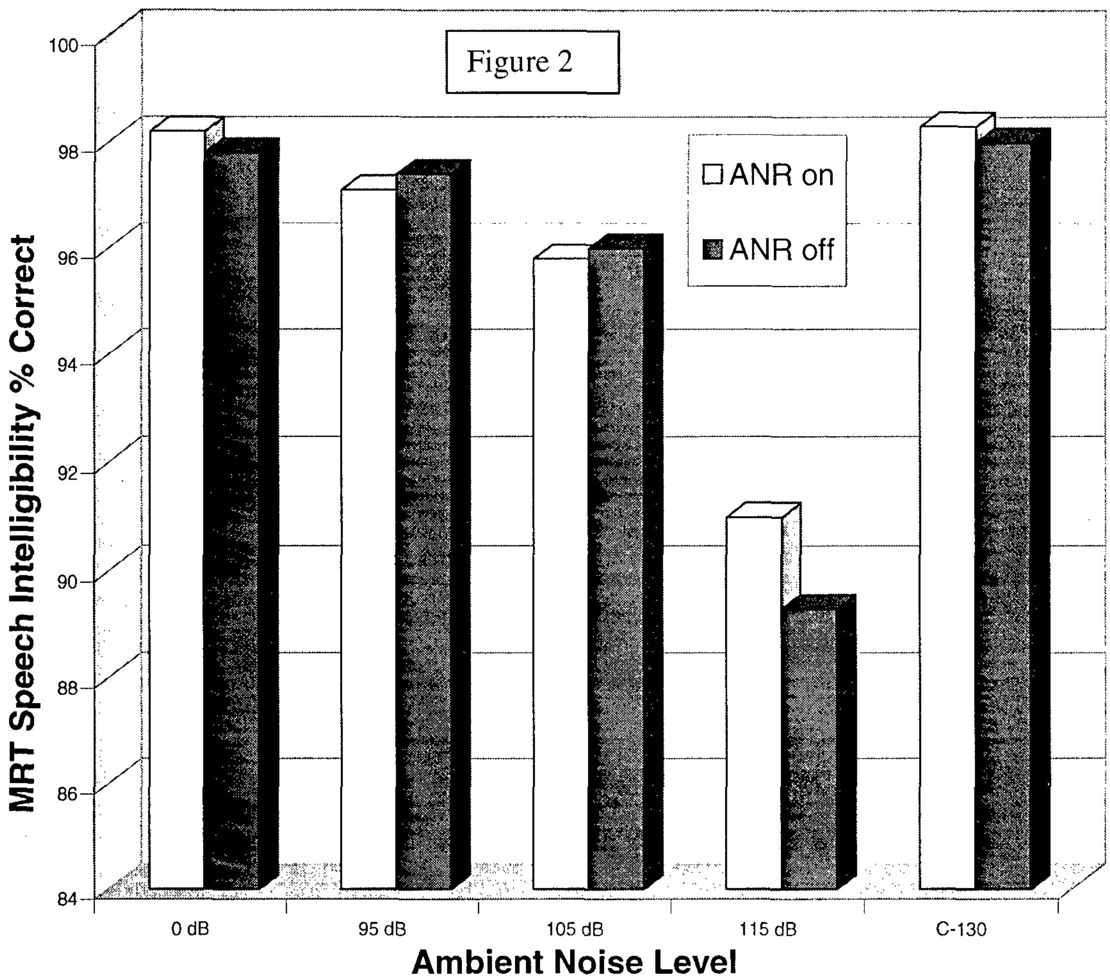
Discussion The intelligibility was controlled by the signal-to-noise ratio at the talker. However, satisfactory communications can be maintained at ambient noise levels up to 115 dB.



Experiment B – Speech intelligibility with Active Noise Reduction (ANR) headsets

Design This experiment used five talkers, three male and two female, and ten listeners, five male and five female. It was a within subjects design, with each subject participating in all experimental conditions. The Modified Rhyme Test (MRT) (ANSI S3.1-1989) was used to measure speech intelligibility. The Bose military PRU-57 ANR headset was operated in both the ANR-on and ANR-off modes. The ANR-on mode achieved an approximate 12 dB reduction in the overall noise level at the ear. The speech levels were approximately equal in both conditions. However, in the ANR-on mode, there is 1-3 dB additive noise in the 1-3 kHz region. The talkers were in a quiet (<45 dB) environment and used H-157 communication headsets including an M-87 noise canceling microphone. The listeners were in a variable ambient noise environment which was an independent variable with four pink noise values (0 dB, 95 dB, 105 dB, and 115 dB) and an additional noise with a C-130 spectrum.

Results The results are shown in figure 2. For ANR conditions the speech intelligibility varied with the ambient noise level. At the 115 dB noise level, the speech intelligibility was above 90% with ANR-on and just below 89% with ANR-off. Similar results were seen with the C-130 noise spectrum.

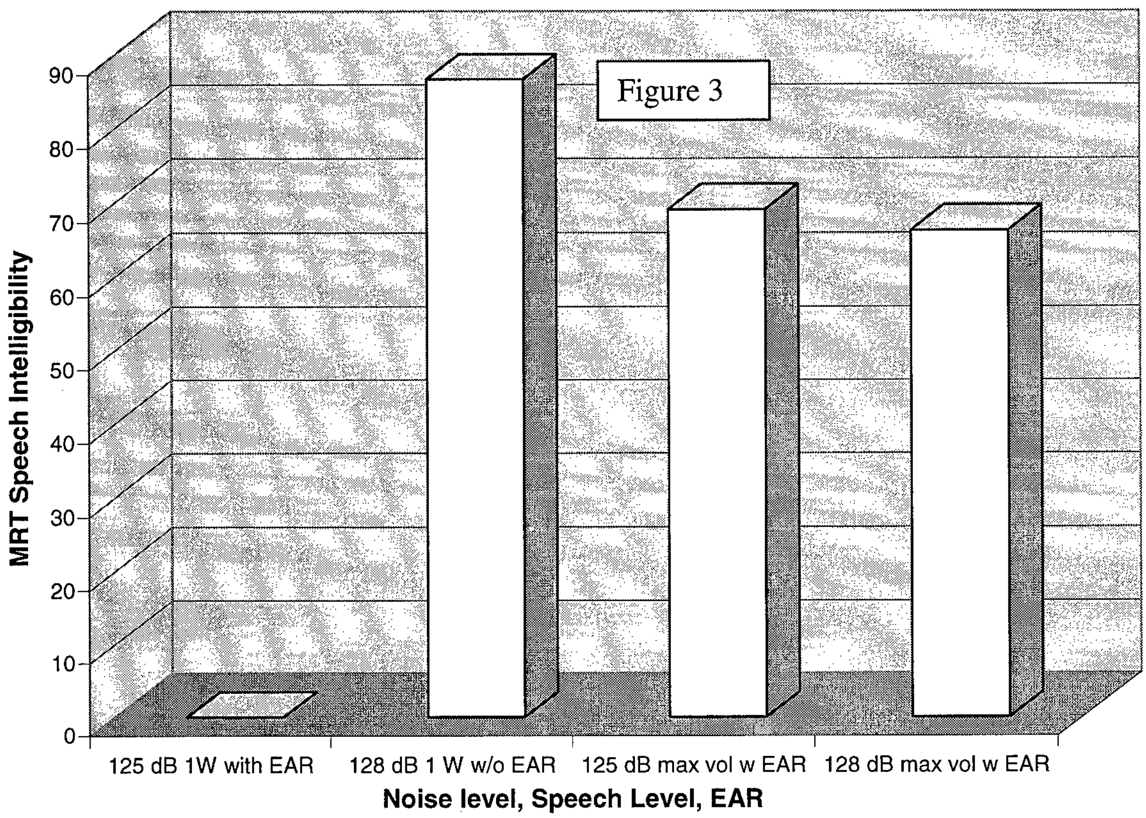


Discussion The intelligibility was controlled by the signal-to-noise ratio at the listener but to a much lesser degree than expected with the ANR headset. Communications were about 10-12% higher than a standard headset, but most of the gain appears to be coming from the improved quality of the speech signal instead of the reduced noise levels produced by the active noise reduction. However, the intelligibility gains are substantial over normal passive noise reduction communication headsets.

Experiment C – Speech intelligibility with EAR earplugs and ANR headset

Design This experiment used five talkers and five listeners, three male and two female. It was a within subjects design, with each subject participating in all experimental conditions. The Modified Rhyme Test (MRT) (ANSI S3.1-1989) was used to measure speech intelligibility. The Bose military PRU-57 ANR headset was installed in a flight helmet (HGU-55/P) and was operated in only the ANR-on mode. The talkers were in a 105 dB pink noise environment and wore flight helmets and oxygen masks with noise canceling microphones. The listeners were in a nearly pink ambient noise environment of 125 dB and 128 dB. Two listening levels were allowed, 1 W total power and maximum volume. The last independent variable was the use of deeply inserted EAR foam earplugs.

Results The results are shown in figure 3. For the 125 dB condition with the EAR plug and with the volume limited to 1 W, the speech was so unintelligible that the subjects could not tell when the speech was presented. The same condition with the volume at maximum resulted in a 69% intelligibility score. When the noise level was raised to 128 dB with the volume still at maximum and using the EAR earplug, the intelligibility decreased to 66%. However, removing the EAR earplug and limiting the volume to 1 W as in the first condition resulted in an intelligibility of 87%.



Discussion Clearly the audio system was unable to deliver sufficiently intense high quality-low distortion speech to overcome the approximately 35 dB attenuation of the deeply inserted EAR earplugs. Obviously, the intelligibility in noise suffered substantially. However, the ANR headset can deliver satisfactory communication intelligibility at noise levels up to at least 128 dB.

EXPERIMENT SUBGROUP 2 – AURALLY-GUIDED VISUAL SEARCH

Equipment

The aurally-guided visual search experiments D & E were conducted in the Air Force Research Laboratory's Auditory Localization Facility (ALF) at Wright-Patterson Air Force Base, Ohio. ALF consists of a geodesic sphere shown in figure 4 of radius 2.3 m, centered within a cubic anechoic chamber with interior dimensions of 6.7 m with 1.3 m fiberglass wedges. The aluminum struts of the sphere were covered with 2.5 cm acoustic foam in order to minimize reflections. Located at each of the sphere's 277 vertices, spaced approximately 15° apart, was a Bose 4.5" Helical Voice Coil full-range loudspeaker (Model 118038) facing the center of the sphere. As shown in figure 5, mounted 5 cm above the anterior surface of each loudspeaker was a square array of light-emitting diodes (LEDs), each of which emitted a 620 nm wavelength light at a luminance of about 200 mL (Perrott, Cisneros, McKinley, & D'Angelo, 1996).

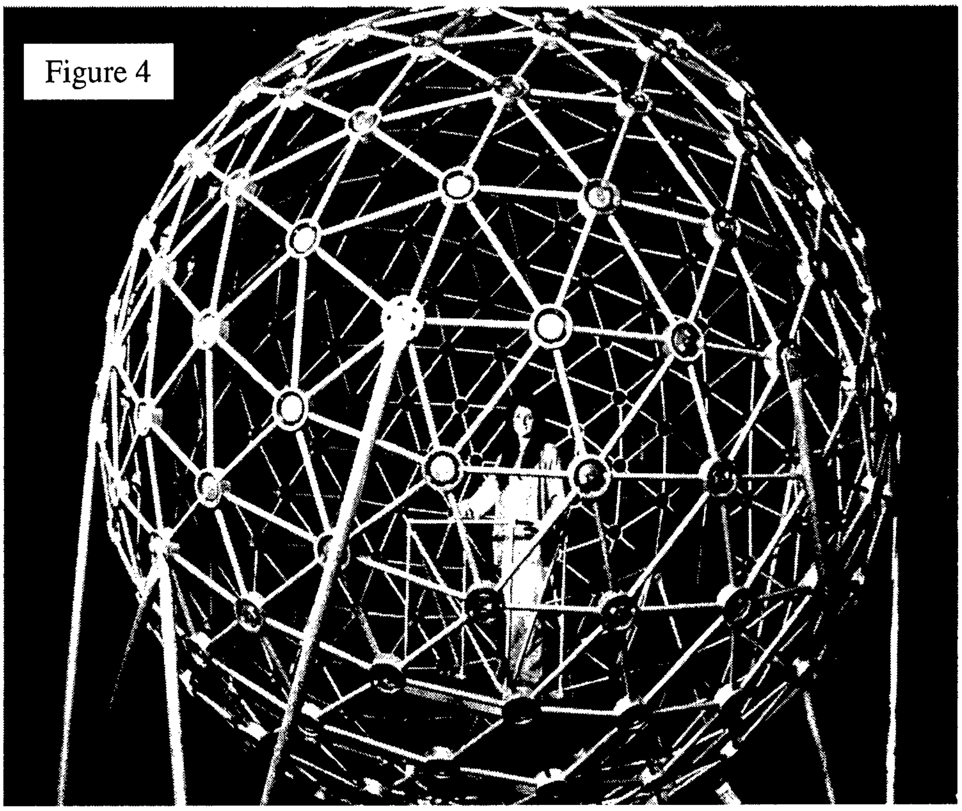
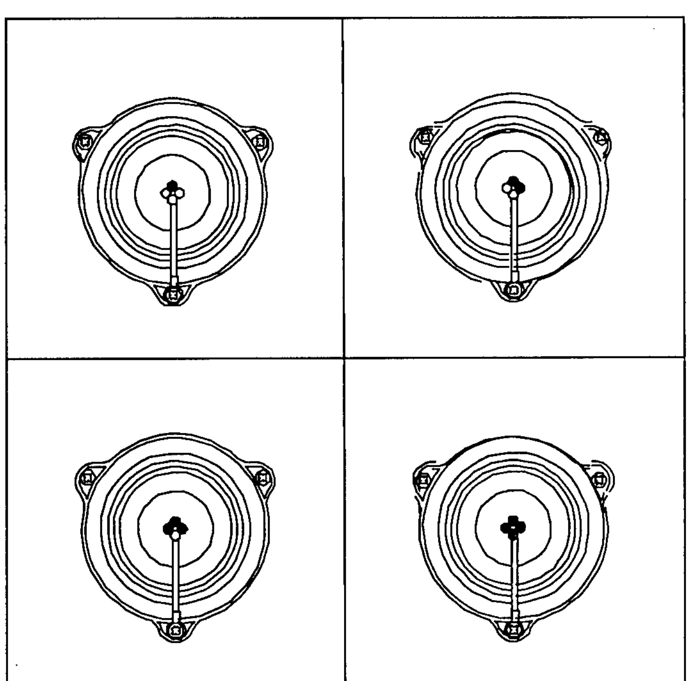


Figure 4

Figure 5



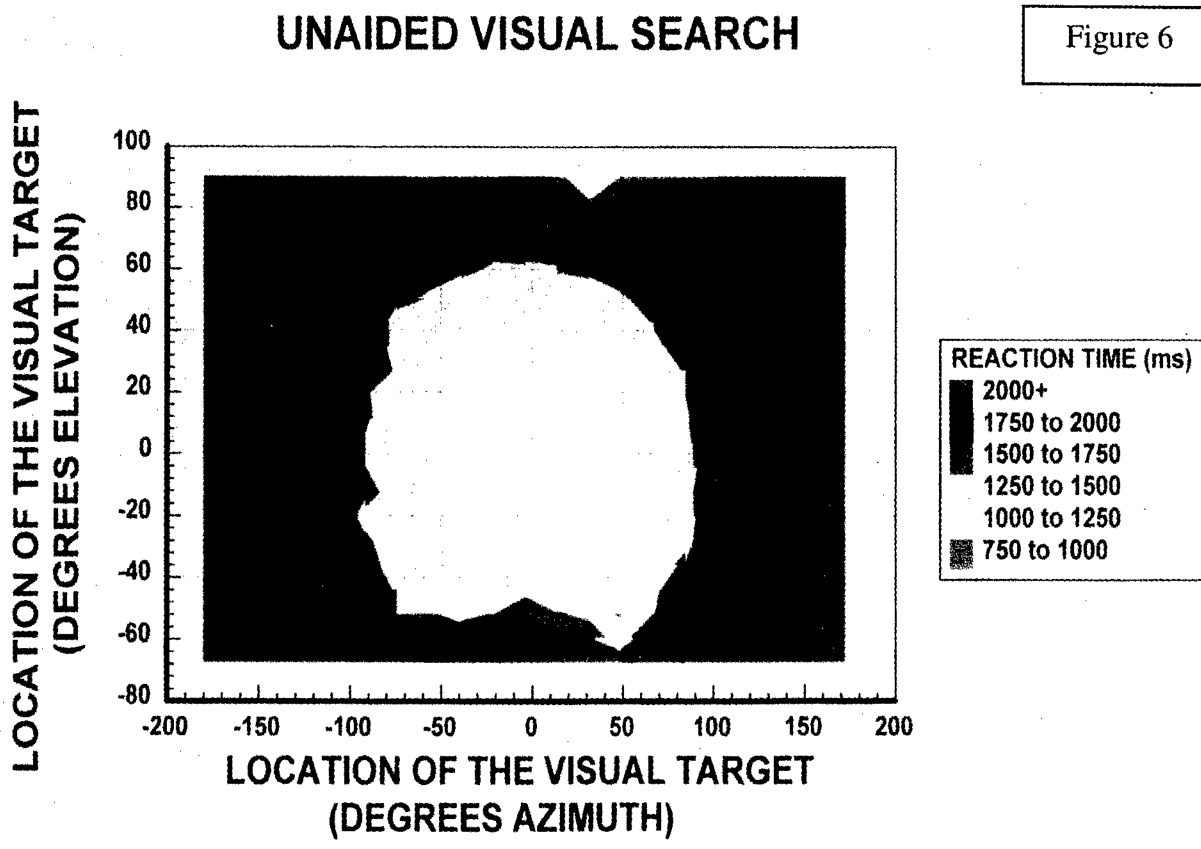
Experiment D – Audio/visual search in a dark field in a real environment

Design A within subjects repeated measures design was used with 528 trials per session and 5 sessions per condition. Six subjects, three male and three female were used in the study. The auditory conditions were no auditory cue, a localized auditory cue via the AFRL–SRL localization cue synthesizer, and auditory cues via the loudspeakers located on the sphere. The auditory stimuli were 250 ms pulsed pink noise with a 50% duty cycle. Therefore the stimuli were on for 250 ms, twice per second. Head motions was measured 60 times per second with a Polhemus 3-Space headtracker. The head motion information was used to update the virtual audio localization cues in real-time.

The subjects fixated at a 0 degree elevation (equator) and 0 degree azimuth location to begin the trial. When ready, the subject determined the number of lights on at the fixation point and responded by pushing one of two buttons indicating the presence of an even or odd number of lights. Immediately the fixation lights were extinguished and a random number of lights came on at a single random speaker location in the sphere. The subject searched the sphere until the single location with lights was located, and then responded odd or even according to the number of lights on at that location. The response time was measured as the time from the fixation response to the correct response to the random stimuli. Errors in response were not counted in the results. However, less than 5% of the responses were incorrect.

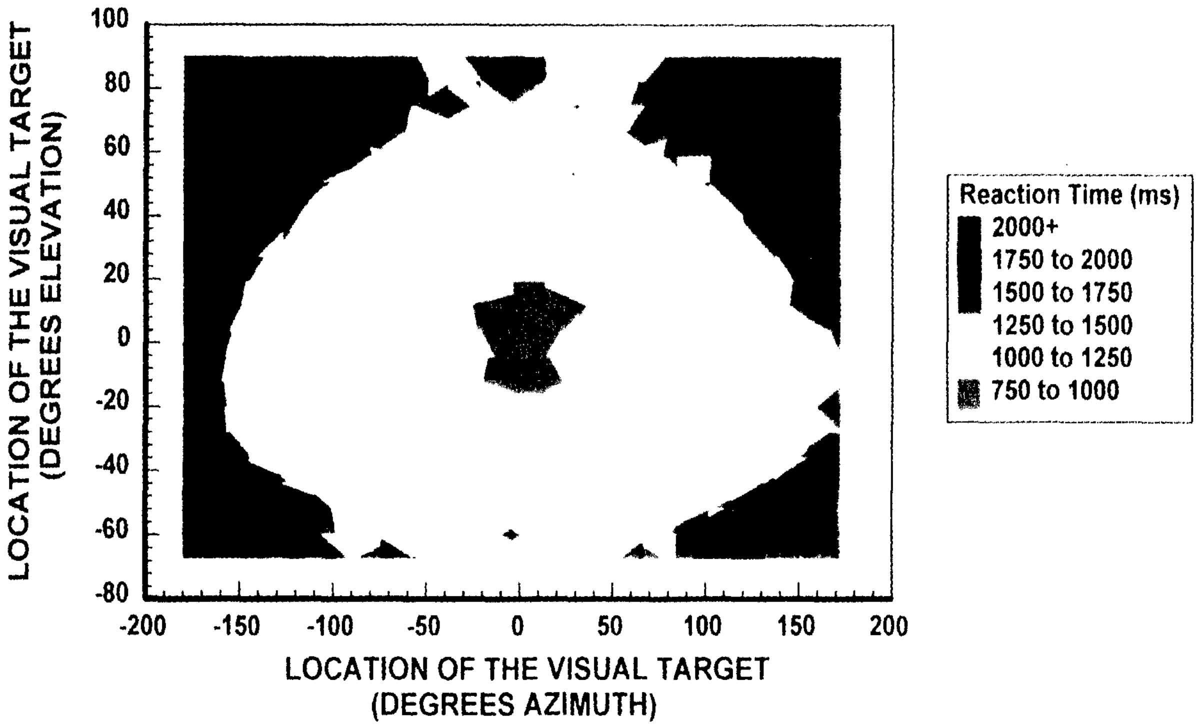
Results Figures 6, 7, and 8 show the response times color-coded in ms for the no audio, virtual headphone audio, and loudspeaker audio conditions respectively. The virtual audio significantly reduces the search time especially at the high and low elevations and in the rear hemi-field. However, the search times are significantly improved in the forward hemi-field. The loudspeaker audio condition displays even faster reaction times, with no times in excess of 1500 ms.

Figure 6



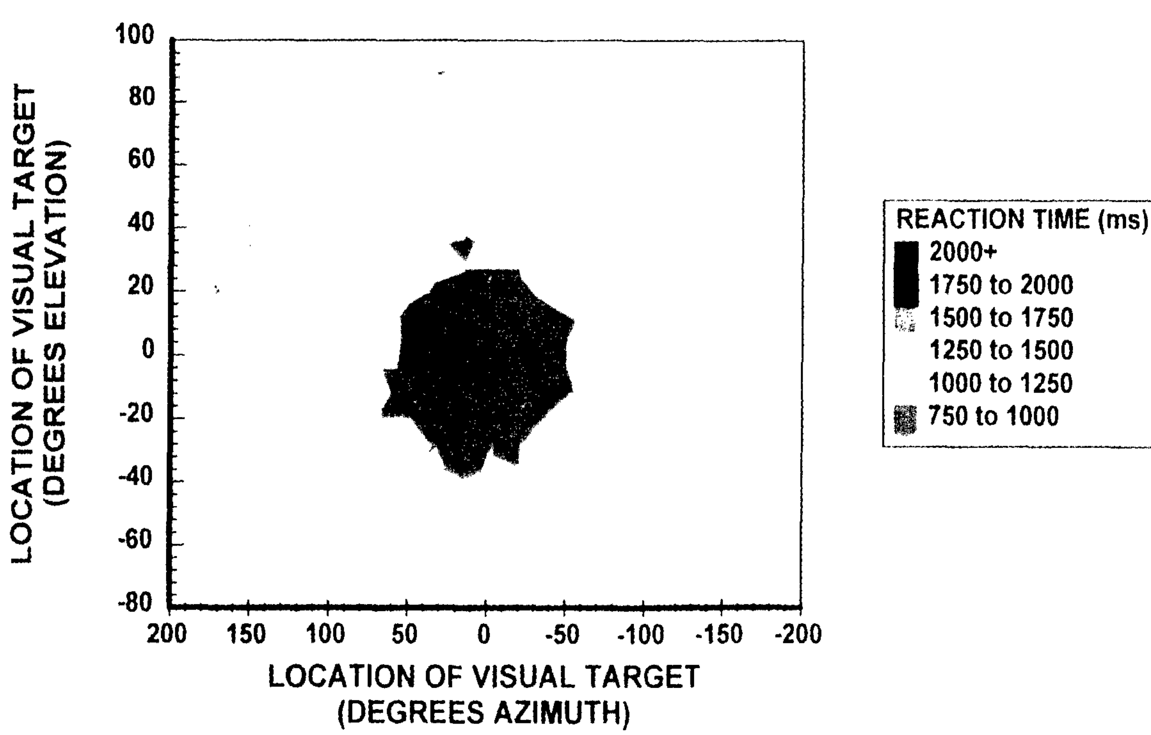
2-D AUDIO AIDED VISUAL SEARCH

Figure 7



LOUDSPEAKER AIDED VISUAL SEARCH

Figure 8

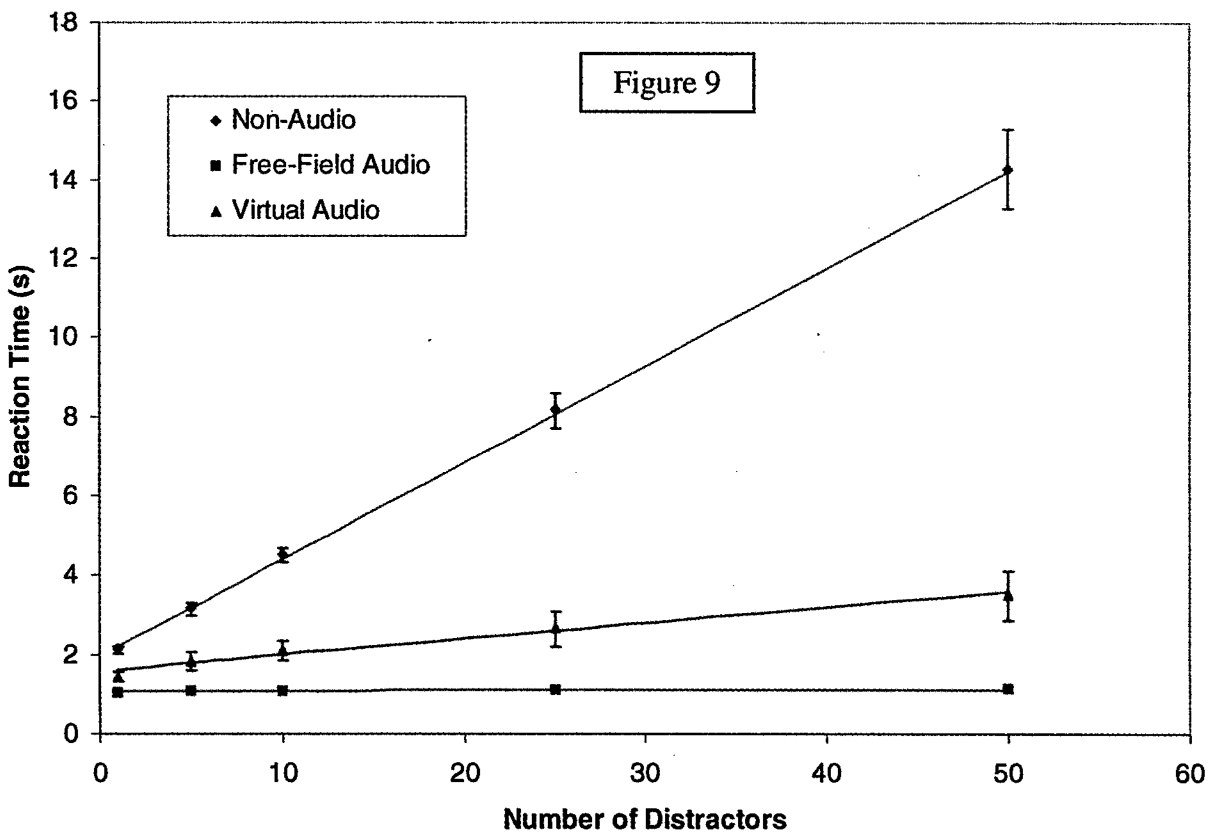


Discussion The results show a clear connection demonstrating that the auditory system can functionally direct the gaze of the visual system. This connection is important from an ecological point of view in that it probably enabled early man to locate prey and avoid becoming prey. The spatial auditory cue enhances the overall performance approximately 50%.

Experiment E – Audio/visual search in a complex visual field in a real environment

Design A within subjects repeated measures design was used with 528 trials per session and five sessions per condition. Five subjects, three male and two female were used in the study. The auditory conditions were no auditory cue, a localized auditory cue via the AFRL–SRL localization cue synthesizer, and via the loudspeakers located on the sphere. The auditory stimuli were 250 ms pulsed pink noise with a 50% duty cycle. Therefore the stimuli were on for 250 ms, twice per second. Head motions and positions were measured 60 times per second with a Polhemus 3-Space headtracker. The head motion information was used to update the virtual audio localization cues in real-time. The visual stimuli were targets of two or four lights in a field of 1 to 50 distractor locations with each distractor location having one or three lights. The simplest case was one target and one distractor. Five different levels of distractors were used, 1, 5, 10, 25, and 50. To begin a trial, the subject fixated at a 0 degree elevation (equator) and 0 degree azimuth location. Once ready, the subject determined the number of lights on at the fixation point and responded by pushing one of two buttons indicating the presence of two or four lights. Immediately the fixation lights were extinguished and a random number of lights came on at two to 50 speaker locations in the sphere. The subject searched the sphere until the one location with two or four lights was located, and then responded two or four according to the number of lights on at that location. The response time was measured as the time from the fixation response to the correct response to the random stimuli. Errors in response were not counted in the results. However, less than 5% of the responses were incorrect.

Results Figure 9 shows the results of the experiment. The visual only search times go up almost linearly with increasing number of distractors. The loudspeaker cue is almost constant at one second. The virtual auditory cue increases only slightly with increasing number of distractors.

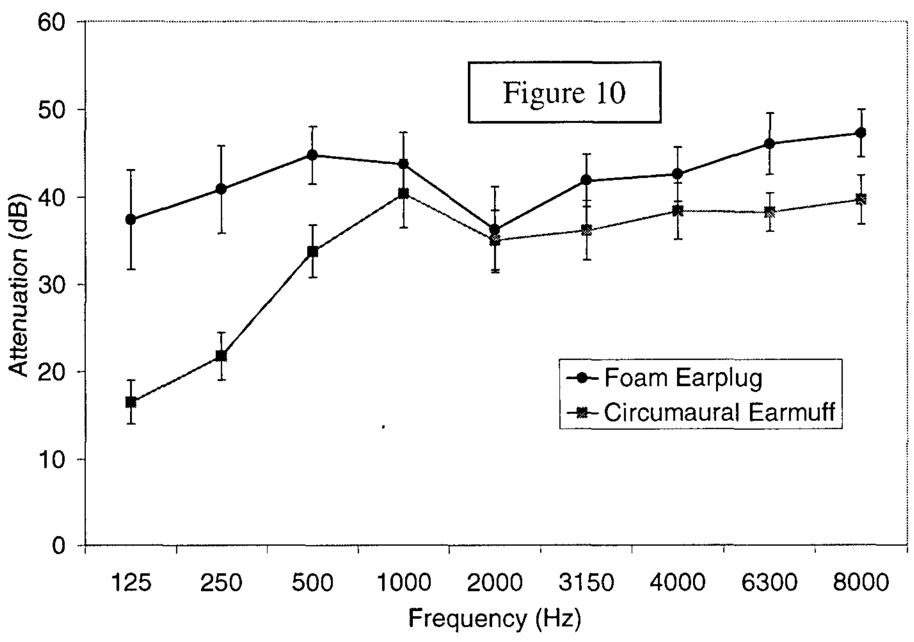


Discussion This experiment clearly shows that spatial auditory cues direct visual gaze in complex as well as simple fields. The fact that the performance with the loudspeaker cue remained constant regardless of the complexity of the visual field is very compelling. It is important to remember that hearing protectors disrupt some of the cues used to localize. Where and how much disruption takes place is of particular importance.

EXPERIMENT SUBGROUP 3 – LOCALIZATION WITH HEARING PROTECTORS

Experiment F – Localization with hearing protectors

Design Two hearing protection devices (HPDs) were employed in this study, the EAR Classic foam earplug and the EAR Model 3000 circumaural earmuff. The nominal attenuation characteristics of these HPDs, as given by the manufacturer, are plotted as a function of frequency in figure 10. Additionally, a non-occluded or no hearing protection condition was included. Localization responses were collected using the God's Eye Localization Pointing (GELP) technique developed by Mark Ericson of the Air Force Research Laboratory and described by Gilkey, et al. 1995. With this method, listeners indicate the perceived location of a sound source by pointing an electromagnetic stylus at the surface of a 20.3-cm-diameter spherical model of auditory space. Two male and four female subjects participated in this experiment. In each of 30 data-collection sessions, 10 for each hearing-protector condition, listeners localized a 750 ms burst of broadband pink noise, presented at 70 dB SPL, from each of the 272 loudspeakers in the sphere. The signal presentation level of 70 dB SPL was chosen in order to be comfortable in the unoccluded listening conditions, but still audible, for all frequency components of the signal, in the occluded conditions. The order in which stimulus locations were sampled was randomized within a session. All experimental data were collected using the GELP technique, described above, with the listener's head fixed by means of a chin rest in order to eliminate head motion as a cue to source location. The ordering of the experimental conditions was randomized. Prior to data collection, all participants were trained extensively on the GELP technique with unoccluded ears and unrestricted head motion. The participants' heads were then fixed using a chin rest, and training continued until performance failed to improve for several consecutive sessions.



Results Figures 11, 12, and 13 show the results of this study. These results point to disturbances in localization performance, in both the horizontal and vertical dimensions. Specifically, the introduction of earplugs or earmuffs occasioned an increase in mean azimuth error on the order of 5°, an increase in mean elevation error of about 15°, and an increase in the percentage of front-back confusions of 24-27%.

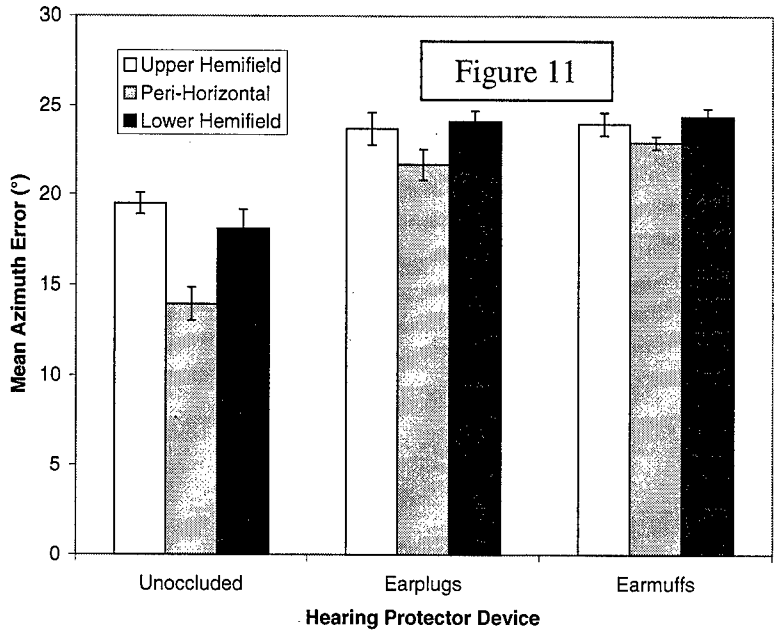


Figure 11
Upper Hemifield
Peri-Horizontal
Lower Hemifield
Mean Azimuth Error (°)
30
25
20
15
10
5
0
Unoccluded
Earplugs
Earmuffs
Hearing Protector Device

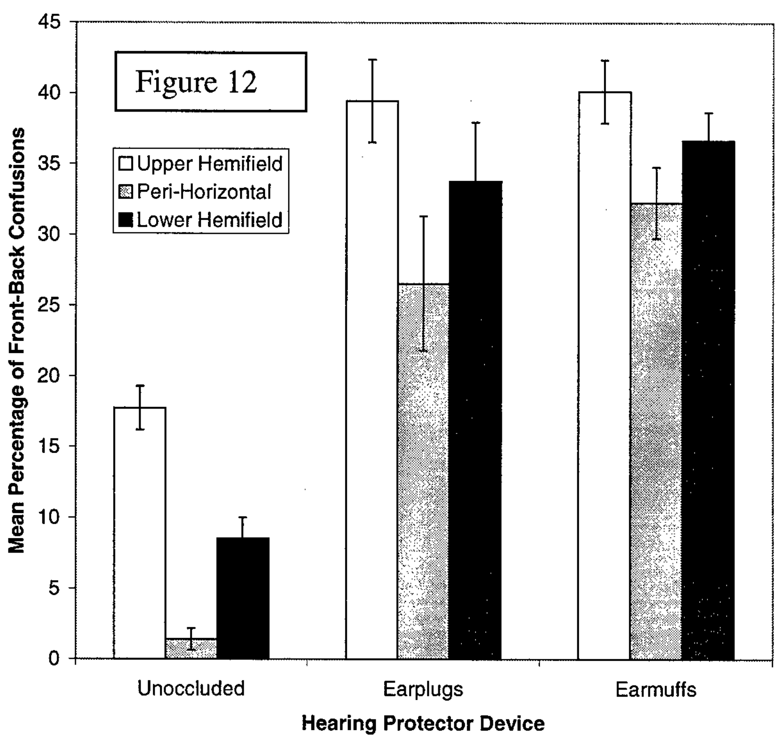
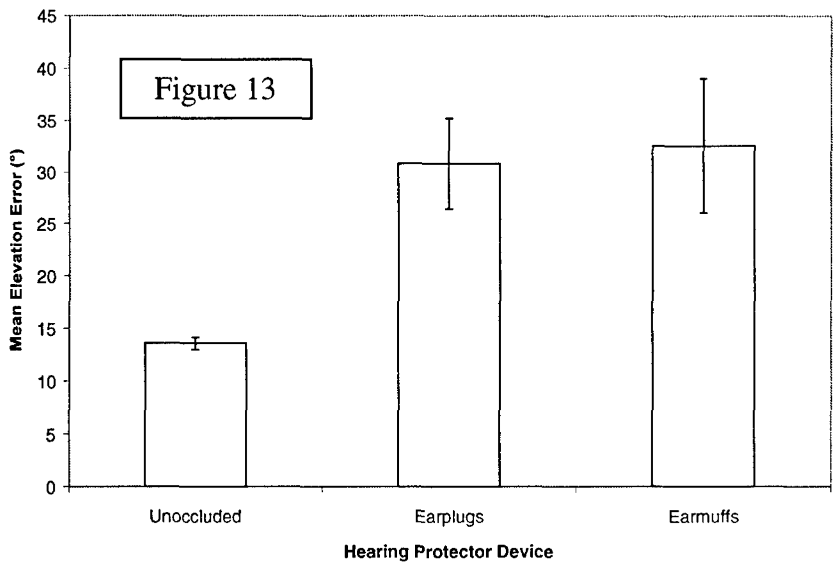


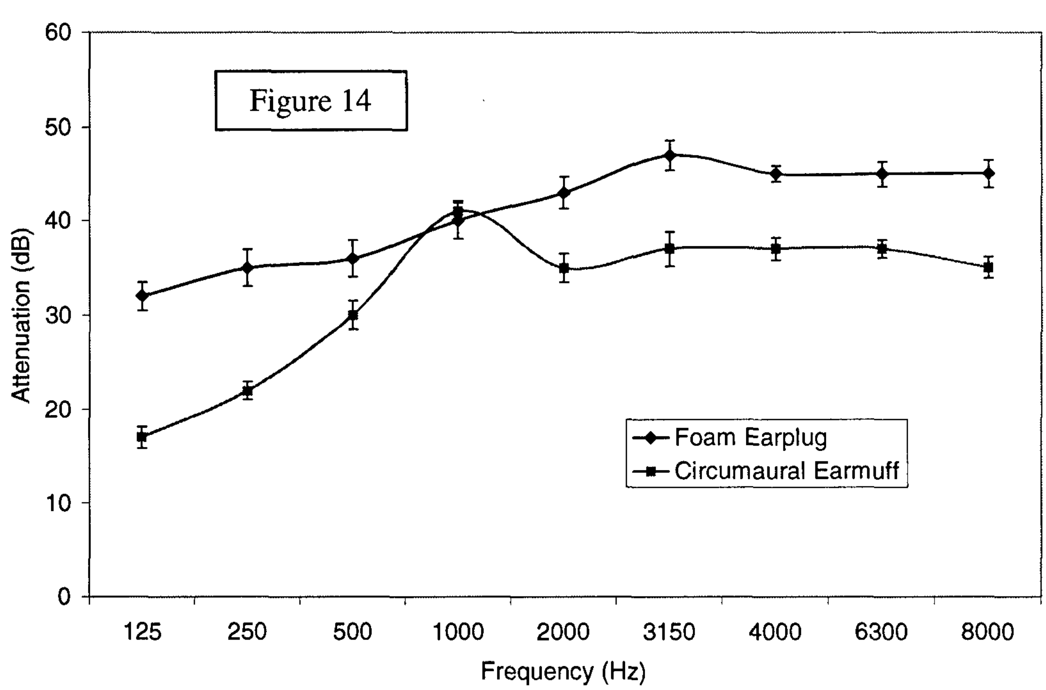
Figure 12
Upper Hemifield
Peri-Horizontal
Lower Hemifield
Mean Percentage of Front-Back Confusions
45
40
35
30
25
20
15
10
5
0
Unoccluded
Earplugs
Earmuffs
Hearing Protector Device



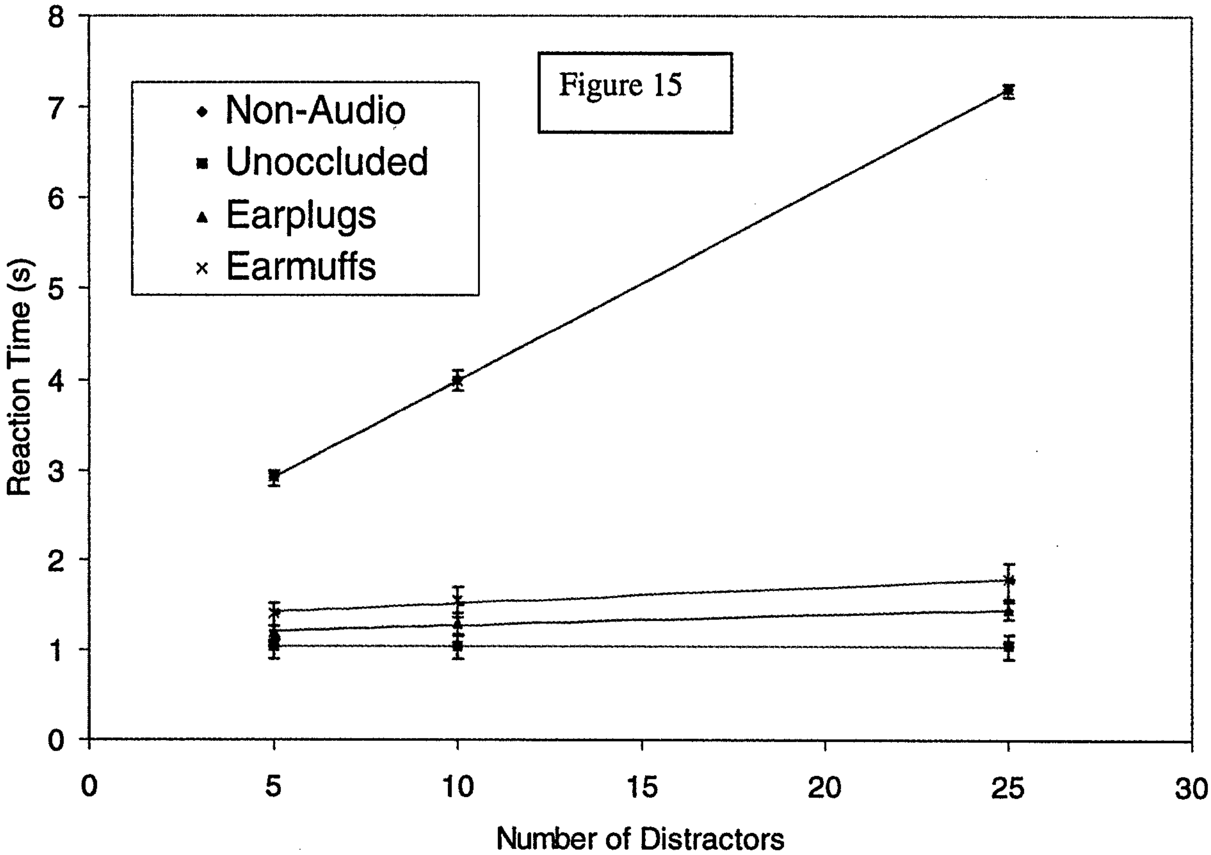
Discussion Localization in both azimuth and elevation are degraded by either earmuffs or earplugs when there is no head motion. This performance degradation is most likely due to the disruption of the spectral cues and the loss of head motion to resolve interaural time delay ambiguity. The performance losses when hearing protectors are worn has many occupational safety implications for both civilian and military users of hearing protectors.

Experiment G – Aurally-guided visual search with distractors and hearing protectors

Design - The EAR Classic foam earplug and the Tasco Sound Shield circumaural earmuff were used in this study. The frequency-dependent attenuation of these devices was measured using the real-ear method (ANSI S12.6-1984), and is depicted graphically in Figure 14. Three subjects, two male and one female, were used in this study. Each had participated in the prior visual search with distractor study describes as experiment E. The same procedures were used in this experiment that were described in experiment E, with the exception that the number of distractors was limited to 5, 10, or 25. The subjects were asked to perform the task with no audio, audio with no hearing protector, audio with the earplug, and audio with the earmuff.



Results The results of this study indicate, as in experiment E, that the visual only search time increases linearly with number of distractors, while the unoccluded search times are constant at about 1 second regardless of the number of distractors. There is only a small effect of the hearing protector, as can be seen by the shallow slope in figure 15.



Discussion The results could be construed as encouraging due to the small (a few 100's of ms) degradation of reaction time in locating the source. But care should be employed. These results were obtained in a laboratory setting with no other noise sources and with substantial visual feedback from the lights. Additional experiments need to be performed investigating the practical auditory localization performance with hearing protectors in a robust visual and acoustic environment.

SUMMARY

This series of experiments has described the impact of hearing protectors, both earplugs and earmuffs, on speech communication capability and on auditory localization. The effects on speech communication are largely negative unless an intense, low distortion, speech signal can be produced at the ear. Clearly this is an area where additional work in developing high-power earphones could benefit a large number of users. Additionally, ANR headsets can improve speech communication capability, but not to the extent that would be predicted from their improved attenuation. This is another area requiring additional research and development. Auditory localization is an inherent part of almost everyone's daily life, improving safety and promoting efficiency. Yet earmuffs and earplugs in some situations seem to seriously degrade localization performance while in others there is little change. This ability to localize acoustic sources is of vital importance in many environments, such as the military, law enforcement, fire fighting, and construction. Once again, additional study is required to resolve the practical issues in this very important area.

ACKNOWLEDGMENTS

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